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A METHOD OF PREDICTING SEISMIC DAMAGE TO RESIDENTIAL-TYPE STRUCTURES FROM UNDERGROUND NUCLEAR EXPLOSIONS

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A METHOD OF PREDICTING SEISMIC DAMAGE TO RESIDENTIAL-TYPE STRUCTURES FROM UNDERGROUND NUCLEAR EXPLOSIONS

Abstract

A method of predicting seismic damage from underground nuclear explosions is discussed. The method is a fast and inexpensive way to estimate damage costs and (although less detailed than more formal methods) it provides a dollar estimate of damages accurate enough for planning purposes.

The two most important factors affecting the amount of damages are magnitude of ground motion and number of structures near the shot. Ground motion response depends primarily on event yield, distance from source to structures, source geology media, and depth of burial (DOB). With these factors known, a method can be developed for determining the pseudo absolute acceleration (PSAA). The number of structures can generally be estimated from the census data for surrounding towns and cities. Complaints and claims for one- and two-story structures can then be estimated from a graph correlating the PSAA and the percentage of structures expected to be damaged.

Introduction

The feasibility of the Plowshare concept of using nuclear explosions for large-scale commercial and industrial purposes depends in part on associated seismic effects. In many cases, the maximum yield that can be employed safely is determined by the "acceptable" amount of damage to nearby structures.

In 1964, Cauthen[1] consolidated all available information on seismic damages caused by the ground motion associated with underground nuclear explosions. Portions of his data were taken from previous high explosive blasting experience. He concluded that damage was independent of frequency and that a peak surface velocity of about 11 cm/sec was the threshold for damage to older homes with plastered interiors. He further concluded that a peak velocity of 20 cm/sec would be the threshold for well-constructed new homes.

As a result of Cauthen's conclusions, only minor damage was predicted for the Salmon Event.* However, Salmon produced 1442 complaints, hundreds more than were predicted. As much of the claimed damage appeared to be credible, and the peak velocities were much lower than 11 cm/sec, a thorough study of the

*Salmon was a 5-kt contained nuclear shot in a salt dome approximately 32 km southwest of Hattiesburg, Mississippi. It was detonated Oct. 22, 1964.

problem was directed by the U. S. Atomic Energy Commission (AEC).

Investigations by the AEC[2] and Power[3] in 1965 indicated that current opinions about structural damage caused by underground nuclear explosions needed to be revised. The threshold of damage could no longer be considered a simple limit of peak ground motion which was independent of structures and ground frequencies.

Wall[4] (1965-1967) observed natural cracking rates by continuously inspecting 43 masonry structures at Mercury, Nevada. His investigation of these selected buildings was also designed to determine the effectiveness of peak-particle velocity as a damage criterion and the least peak-particle velocity which causes architectural damage. The buildings were inspected during periods of no significant nuclear activity. They were also inspected just before and after nuclear explosions.

Wall's findings indicate that masonry structures have a natural cracking rate which results from age, construction standards, traffic, temperature cycling, settling, shrinkage, etc. They also show that this rate is accelerated by the additional ground motion from nuclear events and that cumulative cracks significantly increase after events producing peak-particle velocities of 0.1 - 0.5 cm/sec and higher.

In 1969, Nadolski[5] further studied the architectural damage which seismic disturbances cause to residential structures to develop more meaningful ground-motion damage criteria. Motion records were analyzed for a response spectrum of building motions. With this new response spectrum (which combined amplitude, duration, and frequency of the ground motion), he explained widely varying amounts of damage caused by similar peak-particle velocities. A correlation was made between existing damage and the absolute acceleration. Nadolski further presented a plot of damage complaints versus the pseudo absolute acceleration (PSAA) as an effective damage prediction criterion. His correlations were based on the Salmon Event, high explosives experience, Wall's Mercury study, and the Nevada Test Site (NTS) shots before May 1967.

AEC contractors now perform most of the ground motion and structural damage predictions. One contractor, Environmental Research Corporation (ERC), has studied many aspects of ground motion prediction. In their predictions, ERC's personnel considered source media, coupling effect, travel path of the ground-motion waves, depth of burial (DOB) factor, yield factor, the media at the structures location, etc. Their predictions are made for peak-particle motion at selected locations; pseudo-relative velocity (PSRV) at selected stations; and peak acceleration, velocity and displacement versus slant distance. Their studies and their predictions are published for the AEC as Nevada Operations (NVO) reports.

The Research Division of John A. Blume and Associates (JAB) has developed a procedure for predicting seismic damages which is called the spectral matrix method.[6] This method considers:

- Type and quality of construction
- Condition of the structures to be exposed

- Lateral-force design concept
- Ground-motion frequency content, as compared with the natural frequencies of the structures
- Structural damping
- Soil conditions under the structures
- Duration and magnitude of exposure
- Probable variation from the mean predicted ground motion
- Probable variation from the mean predicted structural response

This work, preshot damage predictions for particular shots, postshot structural damages, and special studies have been published as Nevada Operations (JAB) reports.

Discussion

The methods developed by ERC and JAB for predicting ground motions and corresponding seismic damages are very good, but they are time consuming. Many months are needed to negotiate contracts, to visit the site location, to determine the geology of the area, to make a structural survey, to determine the types and quality of local construction, etc.

With many experiments being conducted under Plowshare at different site locations, it is often necessary to have a quick, inexpensive, relatively accurate estimate of predicted damages. A seismic damage estimate may be needed within a week or so to determine if a particular project will be studied further. Consequently, a method of predicting seismic damages to residential-type structures* has been developed. The method, as discussed in this paper, provides a fast means of predicting seismic damages reliably enough for planning purposes.

Prior to Rulison,† most interest in seismic damage concerned complaints. A complaint may be formal or informal but normally consists of a telephone call to the AEC or its authorized representative. An adjustor (and an engineer, when necessary) investigates, and a claim is filed with the AEC if there appears to be a basis for the complaint. Formal claims are disposed of by payment for repair of the damage, denial of responsibility by an AEC letter, or withdrawal of the claim.

The Rulison Event had a total of 455 complaints filed. Of these, 325 will result in paid claims. The Handley Event (detonated at NTS on March 26, 1970) caused 173 complaints, with 46 claims paid to Oct. 16, 1970. Additional complaints/claims may yet result from Handley because the one-year period for filing claims has not expired. The cost of investigating complaints and of paying legitimate claims must be considered as tangible costs of a particular project.

The only other event resulting in a significant number of paid claims was Salmon (1056 total). However, a

*In this report, residential-type structures include all one- and two-story structures. Churches, gas stations, grocery stores, and other small business structures are included as residential-type structures.

†Rulison was an underground gas stimulation shot fired on Sept. 10, 1969. The project had a design yield of 40 kt and was located near Grand Valley, Garfield County, Colorado.

meaningful correlation of ground motions and damages has not been made because of the many psychological, political, and unknown seismic factors involved. Since major seismic damage was not predicted, an insufficient number of ground-motion measurements were made. Only a portion of the measurements that were made are considered reliable because only displacement records were obtained at Hattiesburg and other points equally distant from the event. Normally, response spectra are developed from strong motion acceleration records.

The most frequent types of damage are architectural in nature (cracked plaster, cracks in swimming pools, broken windows, well or cistern damage, etc.). Most damage occurs to brittle construction materials such as concrete block, plaster board, and brick masonry. The majority of the complaints/claims concern older homes (i.e., homes 10-25 years old), which have already suffered from natural cracking processes. Newer homes are usually strong enough to withstand the additional ground motion caused by a nuclear explosion.

ESTIMATING THE NUMBER OF STRUCTURES

The number of complaints and claims expected is related to the number of residential-type structures in the area. A high-yield shot at NTS will produce only a small number of claims because there are relatively few structures in the affected zone. However, a low-yield shot such as Salmon can result in a large number of claims because of the high density of residential structures in nearby towns and rural areas. Although a structural survey provides an actual count of structures, it is time consuming and costly. The Rulison structural survey[7] was accomplished by using automobiles, airplanes, helicopters, and snowmobiles to reach all areas. Field investigations began Jan. 24, 1969, when much of the area was under deep snow cover, and continued through the spring thaws. The Inventory of Structures for Rulison was published in August 1969.

A faster, if less reliable, estimate of the number of structures can be made from the population statistics of nearby cities, towns, and rural communities. An actual count of structures was made in the Hattiesburg, Mississippi, area[8] and in the Rulison, Colorado, area.[9] By comparing these counts with the best estimates of population for the areas, a population-to-structure ratio is obtained. The Mississippi and Colorado ratios are similar despite the geographical separation between the two states and permit us to generalize. For towns with populations less than 10,000, the ratio is approximately 2.5:1. For cities of 10,000-20,000 it is 2.75:1, and 3:1 for cities over 20,000 population.

The estimate of structures in a rural community depends on the particular region. The rural population of desert-like areas is normally negligible, whereas it may be of considerable importance in farming areas.

The number of structures in farming areas may be estimated by the following method. Census figures usually contain total county populations in addition to the urban and suburban figures. Consequently, an average population density can be obtained by subtracting the city and town

populations from the county population and dividing the remainder by the area of the county. The average population density is divided by the population-to-structure ratio of 2.5:1 for the average density of structures in the county.

In mountainous areas, this method is not practical; much of the land is virtually unsettled. In these areas, the rural population is primarily concentrated in the valleys near the towns. This population cannot be neglected as it may correspond to a sizeable number of structures. It is also very difficult to estimate.

Near small towns, the rural population may equal the town population. Near larger towns and small cities, the percentage living outside the city is smaller. A graph showing one possible interpretation of the rural population in mountainous areas is shown in Fig. 1. These data were obtained from an actual count of structures[7,9] in the Rulison area.

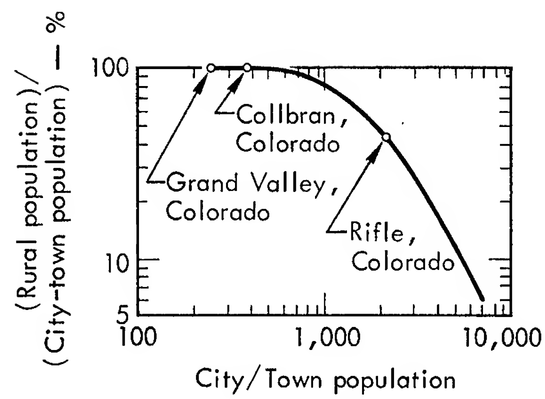

Fig. 1. Rural population in mountainous areas.

GROUND MOTION CRITERION

Use of the PSAA to estimate complaints about underground explosions has been reported by Nadolski.[5] The "Pseudo" in PSAA represents an assumed quantity obtained from only the maximum values (for all times) of the response spectra. The PSAA contains an "absolute" quantity of acceleration. This term correlates structural response and ground motion.

Nadolski used a value of 10% of critical damping to generate his response spectra. Since that time, a 5% damping factor has become the standard reference level in the structural response program for nuclear events.[10] It is a value for which a great deal of spectral response data are already available. A 5% damping ratio is used throughout this report. A 4-way plot of response spectra showing PSAA, PSRV, relative displacement, and period is shown in Fig. 2.

The natural frequencies associated with residential-type structures depend on structural dimensions. A proposed formula, developed by the Joint Committee on the Lateral Forces of Earthquake and Wind of San Francisco (1951),[11] is

$$T = 0.05 \frac{H}{\sqrt{D}} \tag{1}$$

where T = period (sec), H = height of the structure, and D = depth of the structure. For typical residential structures, the period will range from 0.05 to 0.25 sec. The most common values for the period will be 0.10 - 0.20 sec. These correspond to frequencies of 10 to 5 hertz, respectively. Thus, in analyzing past PSAA spectra, only these frequencies are considered.

Previous investigators[1,4,5] have used peak-particle ground motions to identify the magnitude or intensity of the motion.

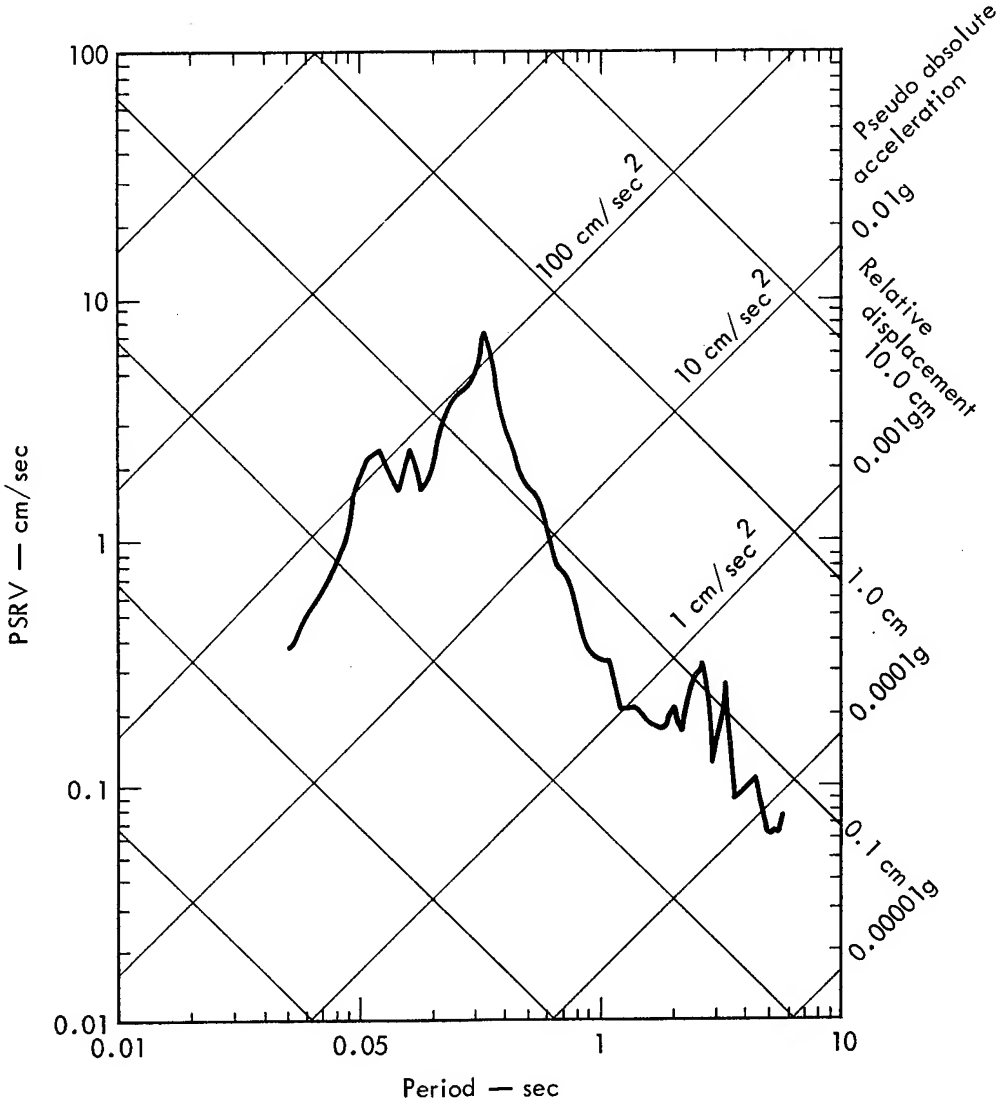

Fig. 2. Observed 5% PSRV spectra for Rulison Event at Station R14 (silt, hard rock, distance 29.74 km).

Most residential structures have natural frequencies different from that associated with peak-particle ground motion. In correlating seismic damage and ground motion, the PSAA values used in this paper are taken from the 4-way plots by averaging ten amplitudes over the period range of 0.10 - 0.20 seconds.

PREDICTING GROUND MOTION

Data from past events will be used to predict the response of future events. The principal factors to be considered are source media, distance between source and structures, event yield, and DOB. If a more elaborate prediction is desired, other factors must also be considered (e.g., transmission path media, coupling effect, media at the recording station).

For a Plowshare Event, location and depth of the nuclear shot are dictated by the intended purpose (the source of the gas field, gas storage area, ore deposit, etc.). The distance between shot source

and structures can be easily determined from maps. The relationship between distance and the predicted PSAA can be seen in Fig. 3. This graph was developed from the data for Rulison,[12] which was associated with sandstone-shale, a design yield of 40 kt, and a DOB of 8440 ft. The line plotted is the least-squares fit to the data.

Future Plowshare Events will require a wide range of yields. A scaling factor must be applied to the PSAA-vs-distance graph for yields other than 40 kt. As expected, larger yields will have larger PSAA values. ERC discusses this yield relationship[13,14] and provides a scaling law which compares any desired yield to that of the Rulison yield:

$$\text{yield factor} = \left(\frac{\text{yield desired}}{40 \text{ kt}}\right)^{0.33} \qquad (2)$$

Similarly, future events will have DOB's different from that used for Rulison. The DOB effect is not as well defined and needs further study. ERC suggests a relationship[13] that compares the desired DOB with the Rulison DOB:

$$\text{DOB factor} = \left(\frac{\text{DOB desired}}{8440 \text{ ft}}\right)^{0.58} \qquad (3)$$

(It should be noted that PSAA increases with DOB.) The PSAA relationships given above have been checked independently for high frequencies and generally agree with the ERC factors.

The Rulison source medium can be described as a saturated shale-sandstone. By scaling other events (e.g., Handley and Piledriver) to 40 kt and 8440 ft, a relationship can be derived for the effect

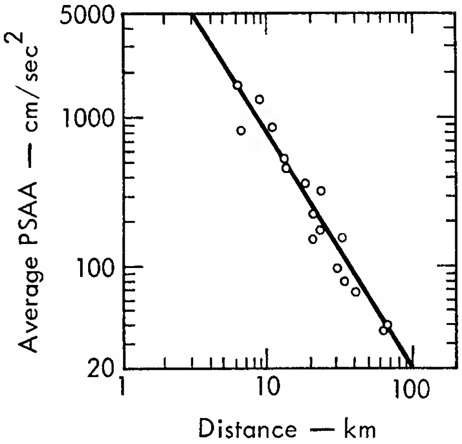

Fig. 3. Distance vs PSAA for 40-kt yield, 8400-ft DOB, and 5% damping.

of source media on the PSAA-vs-distance graph (Fig. 4).

The PSAA value at each structure location (city, town, or area) can be predicted by finding PSAA as a function of distance (Fig. 4) and applying the yield and DOB scaling factors.

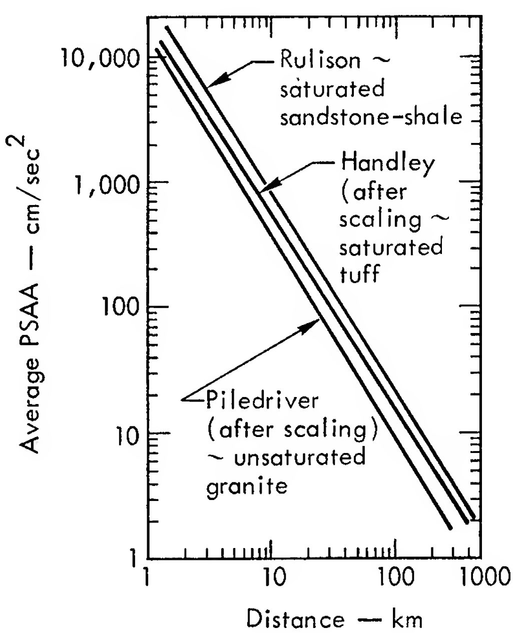

Fig. 4. Distance vs PSAA of Rulison, Handley, and Piledriver Events for 40-kt yield, 8400-ft DOB, and 5% damping.

SEISMIC DAMAGE PREDICTIONS

Damages and PSAA magnitude can be correlated as shown in Fig. 5. To estimate both complaints and paid claims, simply enter the graph with the predicted PSAA and read the corresponding percent of structures affected. It is evident that any specific PSAA will result in more complaints than paid claims. The difference will be the "not credible due to the nuclear event" complaints.

To illustrate damage which is "not credible due to the nuclear event": An investigator arrives at a home to check out a complaint that a plaster wall had been cracked by a nuclear event. The investigator finds that the wall is indeed

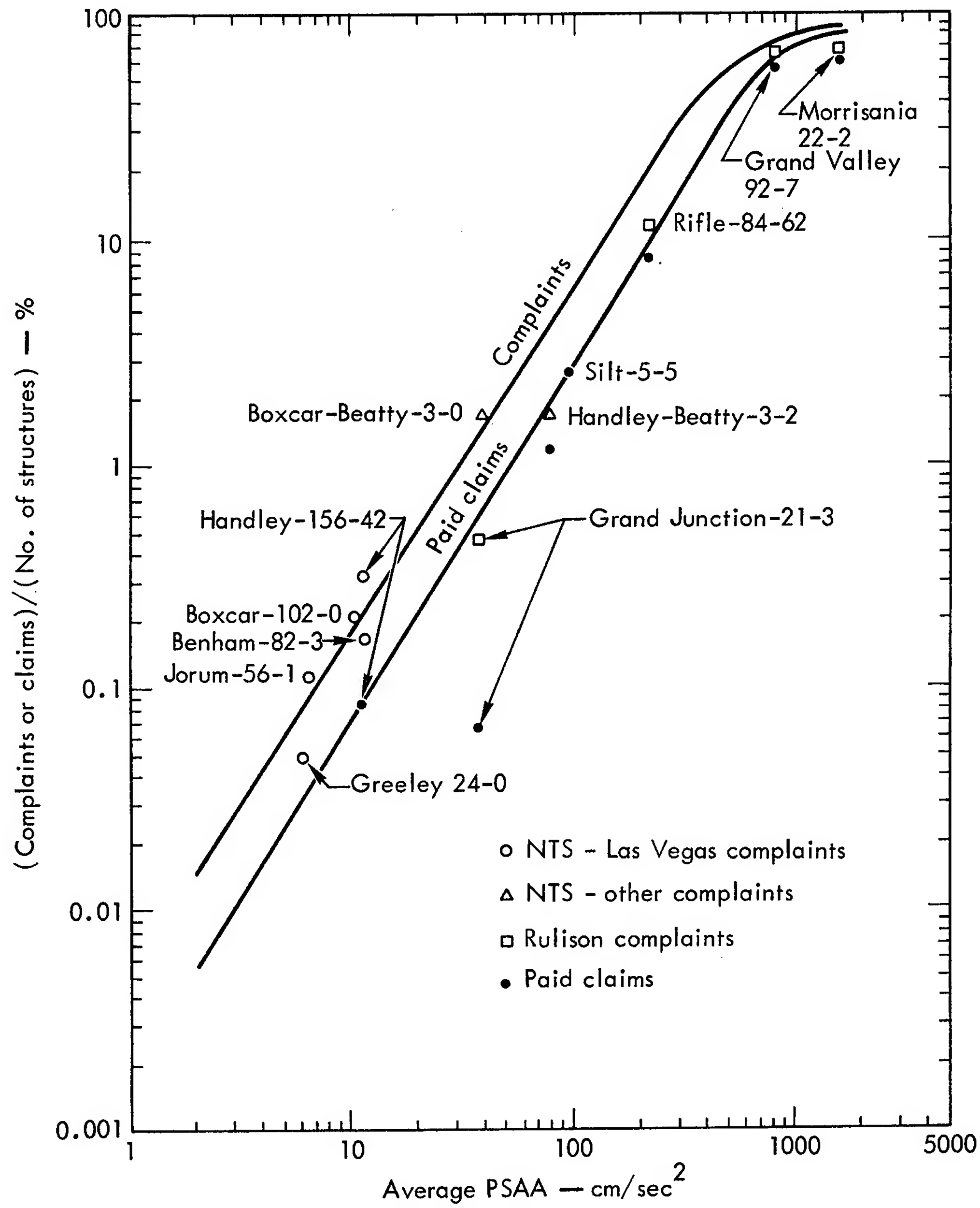

Fig. 5. Seismic damage, complaints, and claims for various nuclear events. (The first number following the name is the number of complaints; the second is the number of paid claims; 5% damping; period range is 0.10-0.20 sec.)

cracked. He also finds that the crack contains spider webs and a thick layer of dust. The event occurred three days ago. The wall was obviously not cracked by the event.

Figure 5 was developed with the reliable data from past nuclear events; it does not include data from Salmon. Data from the NTS events that produced only one complaint in a town or city are not considered since they would not reflect the actual PSAA required to cause one complaint. The Benham and Jorum claim points are not plotted as they would not provide appropriate data for prediction of future claims.

The claim settlement attitude appears to have changed since the Benham Event, and the Handley and Rulison claim data are more appropriate. The Handley data are not complete as the one-year filing period has not passed; figures shown are to Oct. 16, 1970. The Rulison complaint data are complete, and the Rulison paid claim data are to June 30, 1970. Only minor changes are expected to the given Rulison and Handley data.

To obtain a dollar estimate of the damages, multiply the number of paid claims by $400, the average cost to settle past claims. This figure does not reflect administrative costs associated with settling the claims; preshot formal safety investigations; preshot structural surveys; or claims for closing down mines, railroads, and industry during the time of firing the shot.

PSYCHOLOGICAL ASPECTS

Although psychological factors can affect the number of complaints, the psychological effect cannot be predicted. Jackson[15] and King[16] discuss these factors in their papers. A public relations program must be established to describe the seismic probability of damages, Plowshare progress, expected benefits, and the procedures to be followed in the event of seismic damage. An effective program should decrease the number of complaints.

Summary

The method described in the preceding paragraphs is a rapid means of predicting seismic damage from underground nuclear explosions. The principal factors affecting the number of complaints and claims are number of structures, magnitude of the ground motion (determined by the yield), DOB, source media, distance between source and structures, and psychological conditions. The method is based on recorded ground motions and corresponding seismic damages from nuclear explosions. It does not include any inherent conservatism.

Acknowledgments

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Appendix A

AN EXAMPLE PREDICTION

A procedure for estimating the cost of damage at several levels of motion is illustrated in the sample problem shown in Table 1 and Fig. 6. For this example, three different yields at two different DOB's are calculated. The number of paid claims is predicted for two towns and one city with populations and distances from the source as shown in Table 1. The table provides a convenient form to follow for predicting the ground motion and for estimating the number and cost of paid claims.

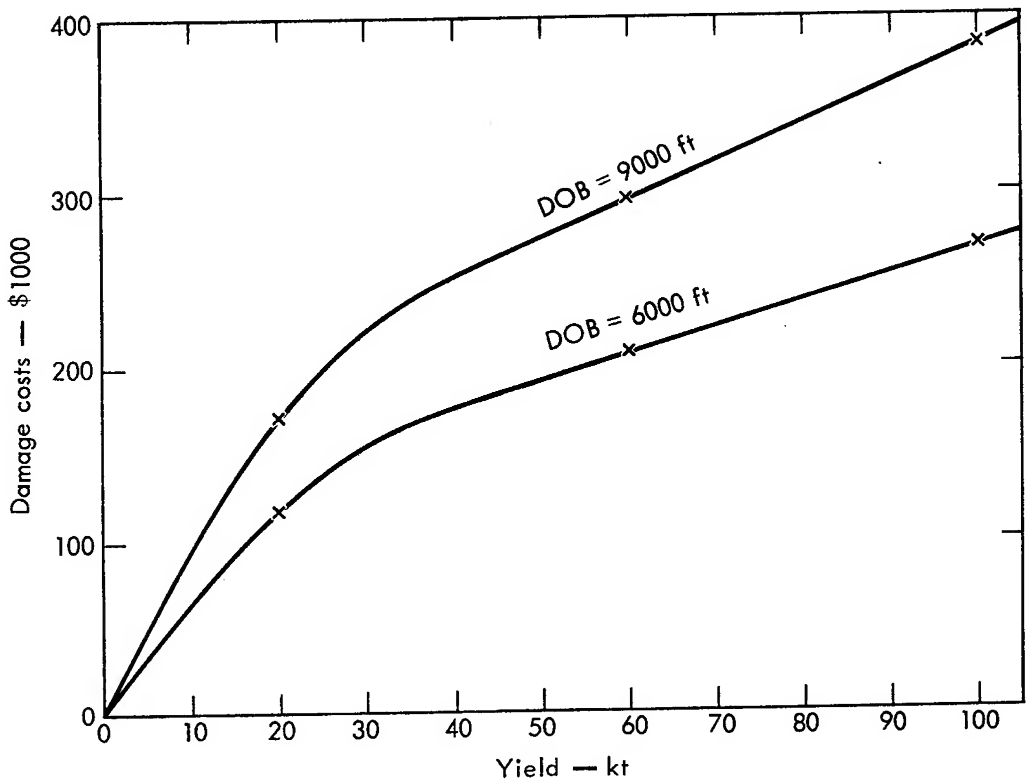

Fig. 6. Damage costs vs yield and DOB.

Table 1. Data for estimating seismic damage from underground nuclear explosions.

City, town, or area	Distance from shot mi	Distance from shot km	Yield (kt)/ DOB (ft)	Predicted ground motion: Distance for yield = 40 kt DOB = 8400 ft	Yield factor	DOB factor	Estimated PSAA (cm/sec^2)	Estimated No. of claims: Population	Estimated No. of structures	Structures damaged (%)	No. of claims	Cost of claims ($)
			20/6000		0.80	0.82	344			19.5	47	18,800
			60/6000		1.15	0.82	494	300	120	34.0	82	32,800
Town	8	12.8	100/6000	525	1.36	0.82	584	PLUS	+120	44.0	106	42,400
A			20/9000		0.80	1.04	436	RURAL	240	27.5	66	26,400
			60/9000		1.15	1.04	627			46.0	110	44,000
			100/9000		1.36	1.04	745			55.0	132	52,800
			20/6000		0.80	0.82	236			10.7	145	58,000
			60/6000		1.15	0.82	340			19.0	256	102,400
			100/6000		1.36	0.82	400	2500	1000	24.5	331	132,400
Town	10	16	20/9000	360	0.80	1.04	300	PLUS	+350	15.7	212	84,800
B			60/9000		1.15	1.04	430	RURAL	1350	27.0	365	146,000
			100/9000		1.36	1.04	510			35.5	479	191,600
			20/6000		0.80	0.82	82			2.0	102	40,800
			60/6000		1.15	0.82	118			3.5	179	71,600
City	20	32	100/6000	125	1.36	0.82	139	14,000	5100	4.6	234	93,600
C			20/9000		0.80	1.04	104			2.9	148	59,200
			60/9000		1.15	1.04	150			5.2	265	106,000
			100/9000		1.36	1.04	177			6.8	347	138,800
			20/6000								294	117,600
			60/6000								517	206,800
			100/6000								671	268,400
TOTALS			20/9000						8140		426	170,400
			60/9000								740	296,000
			100/9000								958	383,200

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